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Material characterisation and numerical modelling of gypsum plasterboards in fire. In
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(FIRST PAGE OF ARTICLE)

ABSTRACT

The fire resistance characteristic of LSF wall systems mainly depends on the protective linings in use, commonly gypsum plasterboards. However, unclassified boards with varying composition and more notably with ambiguous thermal properties are increasingly becoming available in the market. Therefore a study was undertaken with an aim to set minimum standards for fire protective boards used in LSF wall applications. This paper presents the details of this study based on material characterisation and finite element thermal modelling of the most commonly used fire protective board, gypsum plasterboards, to address these critical issues related to fire safety design. In the material characterisation phase of this study, thermal properties of three different gypsum plasterboards manufactured in Australia were measured, analysed and compared. Subsequently, it proposes a thermal property based "k-factor" capable of giving an overall measure of the fire performance of boards, so that it can be used in appropriately classifying fire protective boards. As it is not known how this factor relates to the overall fire performance of LSF wall systems, numerical models were also developed and used to simulate the performance of LSF walls exposed to the standard fire. Finally, a correlation between time-temperature profiles from numerical analyses and calculated k-factors was established.

INTRODUCTION

Buildings must be designed and constructed to meet acceptable standards of structural adequacy, safety, health and services. Fire safety is considered as one of the most important criteria of a building. In the Building Code of Australia [1] light gauge steel framed (LSF) wall systems protected with plasterboards are identified as continuous fire rated barriers for compartmentalising buildings against fire incidents. The code requires certain Fire Resistance Level (FRL) for them to be used as

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construction elements. AS 1530.4 [2] provides suitable guidelines for determining this FRL of construction elements. FRL is expressed in minutes and is determined based on three criteria; structural adequacy, integrity and insulation.

The steel frame of LSF wall systems is made of thin-walled cold-formed lipped channel section (LCS) studs and unlipped channel section tracks. When exposed to fire conditions, these thin-walled steel stud sections heat up rapidly and reach their failure temperatures quickly. It will eventually lead to structural instability of the building. Therefore, fire resistance of load bearing LSF wall systems mainly depend on the protective linings in use, i.e. fire protective boards, which keep the steel stud temperatures from reaching their limits. Fire rated gypsum plasterboards are the most commonly used type of boards as protective lining for LSF wall systems.

However, unclassified plasterboards with varying composition and more notably with ambiguous thermal properties are increasingly being used in recent times. Hence there is a need to set minimum standards for fire protective boards based on their thermo-physical properties in order to ensure appropriate fire protective boards are used to enhance fire safety. There is also a need to study the effect of these thermal properties on the FRL of LSF walls and develop a method to calculate FRL based on thermal properties. Hence a study was undertaken based on material characterisation and finite element thermal modelling of the most commonly used fire protective board, gypsum plasterboards, to address these critical issues on fire safety design.

MATERIAL CHARACTERISATION

The main constituents of gypsum plasterboard is Calcium Sulphate Di-hydrate ($CaSO_4 \cdot 2H_2O$). The percentage of pure gypsum (i.e. $CaSO_4 \cdot 2H_2O$) within can vary between 60 – 100% depending on the manufacturer [3]. This pure gypsum contains approximately 20.9% chemically bound water. Additionally, about 3–4% free moisture content is present within the pores of gypsum core [4]. Fire retarding property of gypsum plasterboards is mainly related to its delayed temperature evolution across the depth of plasterboard due to the energy absorption for evaporation of free water and crystalized water of gypsum ($CaSO_4 \cdot 2H_2O$). Supplementary to gypsum, the composition of commercial plasterboards consists of three other categories of constituents which are accountable for adjusting shrinkage, maintaining integrity, and providing low thermal conductivity of the end product exposed to fire. Vermiculite, glass fibres and fillers are used respectively under the above categories.

In this material characterisation phase of the study, chemical composition and thermal properties of three different gypsum plasterboards manufactured in Australia were measured, analysed and compared.

Chemical Composition Characterisation

As the amount of gypsum varies among different boards, and specific chemical identity and/or exact percentage of composition are not available, the powder X-ray diffraction (PXRD) analysis was undertaken in this study. X-ray diffraction patterns were collected with a PANalytical X'Pert Pro diffractometer using cobalt Kα radiation, and the data was analysed using JADE and Highscore Plus for phase identification, and TOPAS for quantitative phase analysis using the Rietveld method.

Table 1 shows the composition analysis from PXRD analysis at ambient temperature. It reveals significant differences in the composition of the three boards although they are considered equivalent in terms of FRL. Scanning electron microscopy (SEM) images from TM3000 was used to view the crystalline structure of the constituents of gypsum plasterboards. The specimens were freshly cracked to obtain best images.

TABLE I: COMPOSITION FROM PXRD ANALYSIS

Components	Board 1	Board 2	Board 3
Quartz	0.6	1.2	1.4
Aragonite	2.4	3.3	3.4
Anhydrite	1.5	1.3	1.9
Bassanite	2.2	8.8	1.2
Gypsum	83.9	65.0	84.4
Vermiculite	1.7	0.8	
Sepiolite	5.7	7.0	
Non-diffracting/unidentified	2.0	12.7	7.8

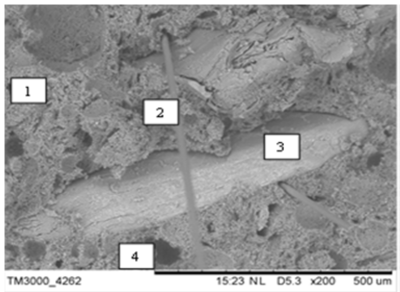
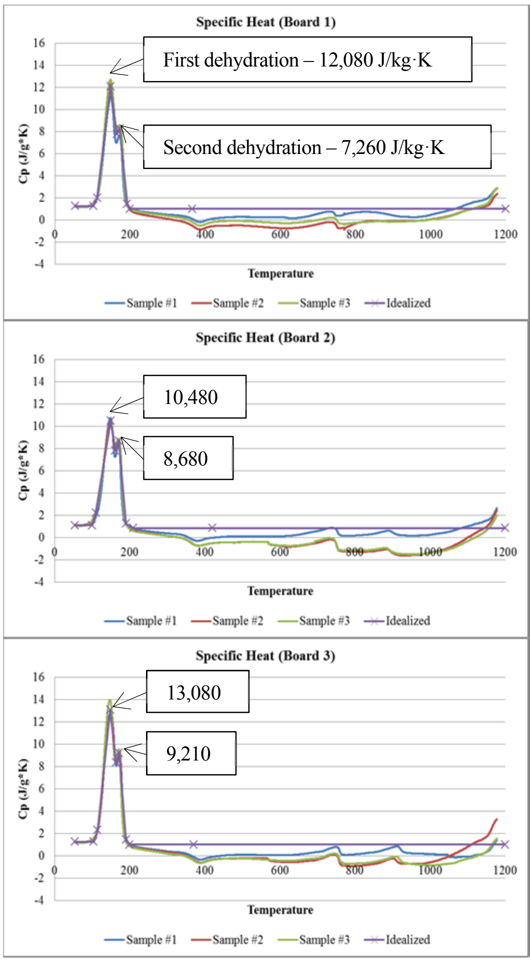


Figure 1: Crystalline structure 1) gypsum, 2) glass fibre, 3) vermiculite,

Thermo-physical Characterisation

Specific heat (C_p), mass loss/relative density, thermal conductivity and linear thermal expansion variations with temperature were measured for thermo-physical characterization of the three gypsum plasterboards. Simultaneous thermal analyzer (NETZSCH STA 449, F3), laser flash apparatus (NETZSCH LFA 457) and dilatometer (NETZSCH DIL 402C) were used to measure these thermal properties. For the first three properties 20 ºC/min heating rate was used while linear thermal expansion was measured at 5 ºC/min heating rate (maximum for the instrument). Powdered samples were used in STA measurements (Pt crucibles with pin holed lids) while solid board samples were used in both LFA and DIL. Figures 2 to 5 show the measured thermal properties as functions of temperature for the three boards.

All the samples exhibited similar specific heat versus temperature characteristics with two peaks. The dehydration process of the chemically bound water contributes to these peaks. The board with the largest gypsum content (Board 3) shows the highest peak values of 13,080 J/kg/ºC at 148 ºC and 9,200 J/kg/ºC at 172 ºC. The higher the peak specific heat the more energy the gypsum plasterboard can absorb, and thus the heat transfer across the wall will be delayed. Thus Board 3 is likely to perform better, however, the overall thermal performance will depend on all three thermal properties. A mass reduction of 16–17% occurs with dehydration reactions at temperatures between 115 and 180ºC, while another 6–8% mass reduction occurs at 650ºC following an almost constant relative density. As seen in Figure 3, the mass loss of these plasterboards is small and thus the effects of cracking and shrinkage will be minimised beyond 650ºC. The boards that exhibit rapid reduction in density are likely to cause premature integrity and insulation failures, and must be avoided. Further, thermal expansion results (Figure 5) of Boards 1 and 2 show that overall cracking and shrinkage characteristics will be improved due to the expansion of vermiculite in these boards. Test results showed that thermal conductivity at room temperature is 0.25 W/m/ºC. The thermal conductivity values decreased to 0.12 W/m/ºC at about 200ºC due to dehydration reactions with hardly any variation among the three boards. Beyond this, the thermal conductivity increases due to the ablation process caused by burning of plasterboard outer layers and exhibit a sudden increase at about 900ºC due to intense cracking.



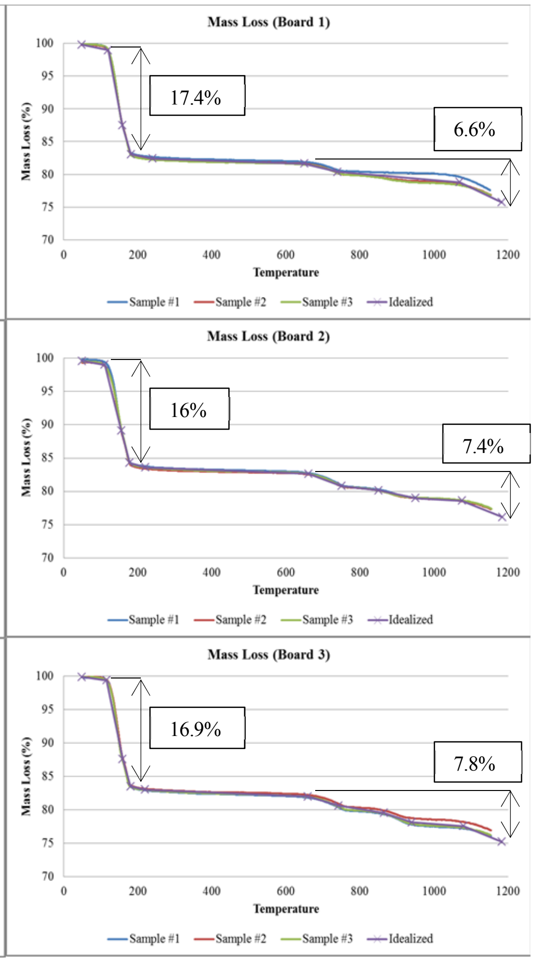
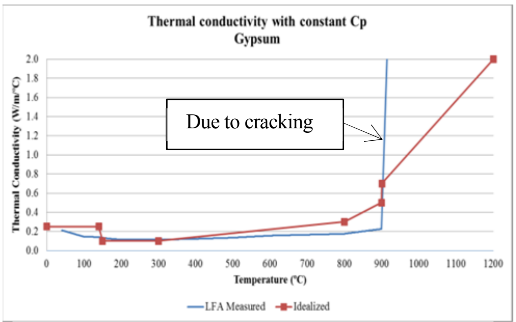


Figure 2: Specific heat variation

Figure 3: Mass loss variation



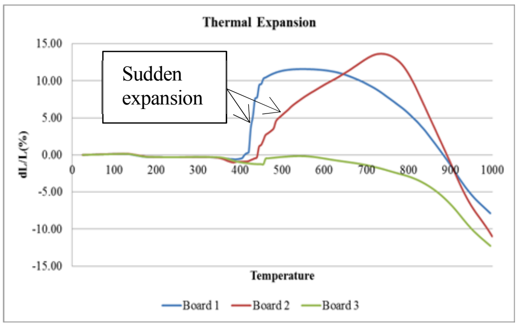


Figure 4: Thermal conductivity variation

Figure 5: Thermal expansion

Overall Fire Performance Index (k-factor)

As discussed above, the overall fire performance of a certain gypsum plasterboard depends on all the three thermal properties. Hence this paper proposes a “k-factor” and its variation with temperature as an overall measure of the fire performance of boards that can be used as a standard to appropriately classify fire protective boards. The k-factor (Equation 1) is based on thermos-physical properties and is defined as a function of specific volumetric enthalpy (E(T) in J/m^3), specific heat (C_p(T) in J/(kg^{o}C)), density (ρ(T) in kg/m^3) and thermal conductivity (λ in W/m/K) at temperature T (T_A - ambient temperature). However, this does not account for the extensive ablation and subsequent integrity failure of plasterboards due to excessive mass loss. Therefore, using the results given in Figure 3, it is proposed that the total mass loss by 1200 °C and the mass loss by 200 °C are limited to 25% and 20% from the initial value, respectively.

$$k = \frac{E(T)}{\lambda} = \frac{\int_{T_A}^{T} C_p(T)\rho(T)dT}{\lambda} \quad (1)$$

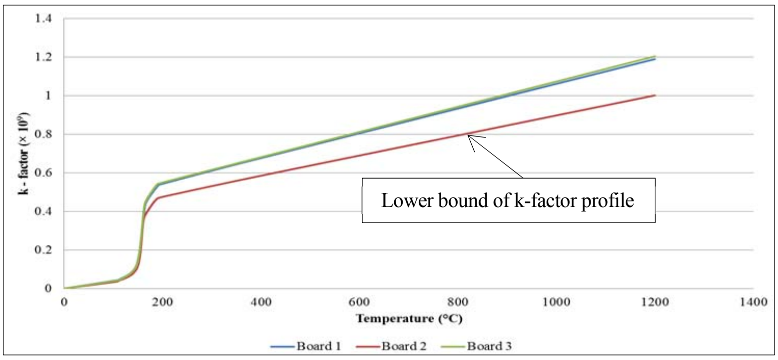


Figure 6: Variation of k-factor with temperature

As illustrated in Figure 6, the k-factor profiles of the three boards calculated based on Equation 1 showed a similar trend with increasing temperature, however, it is not known how they relate to the overall fire performance (FRL). Therefore numerical models were developed to simulate the performance of LSF walls exposed to the standard fire to establish a relationship between k-factor profiles and FRL.

FINITE ELEMENT THERMAL MODELLING

Finite element (FE) thermal modelling has been widely used for predicting the thermal performance of LSF wall systems instead of the expensive and time consuming full-scale fire tests. In this study, 3-D FE heat transfer model was developed as shown in Figure 7 to simulate the performance of LSF walls exposed to the standard fire. For this purpose the LSF wall with single 16 mm plasterboard lining was simulated using the heat transfer model developed with Abaqus/CAE Version 6.14-2 [5] and was validated using Kolakar's [4] fire test results. The simulated wall configuration was of single plasterboard (1 x 16 mm) and lipped channel section studs of 90×40×15×1.15 mm. The model development was undertaken using 8-node linear heat transfer brick elements (DC3D8) and a global mesh density of 20 mm was used with solid sections. Tie constraints were defined at the interface to facilitate the solid to solid heat transfer. The thermo-physical properties proposed in Keerthan and Mahendran [6] for Australian manufactured gypsum plasterboards and properties given in the Eurocode 3 Part 1-2 for steel were used as the inputs for FE heat transfer model validations. The three heat transfer modes viz. conduction, convection and radiation are integrated in FE modelling. The conduction was defined under material properties as thermal conductivity. The effects of convection and radiation for heat transfer were defined by assigning appropriate convective film coefficients (exposed = 25, unexposed = 10 W/m^2°C) and emissivity values (exposed, unexposed , cavity = 0.9). The standard fire curve was assigned to the fire exposed side as a boundary condition using an amplitude curve of time-temperature profile of ISO 834 standard fire curve. The temperature of fire exposed side was allowed to follow the amplitude curve by assigning unity to sink temperature. The initial temperature of the models was assigned by defining a pre-defined field for entire model at ambient temperature, 23°C. Further, the Stefan-Boltzmann constant of $5.67\times E^{-8}$ and absolute zero temperature of -273 °C was assigned to the models. As illustrated in Figures 8 and 9 FE analysis results showed a good agreement with Kolakar's (2010) results.

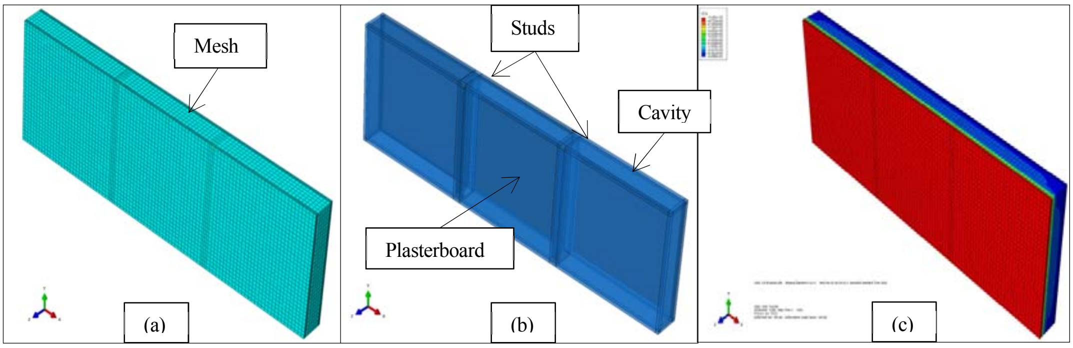


Figure 7: 3D FE model of LSF wall (a) mesh details, (b) wall model (c) temperature contours 60 min

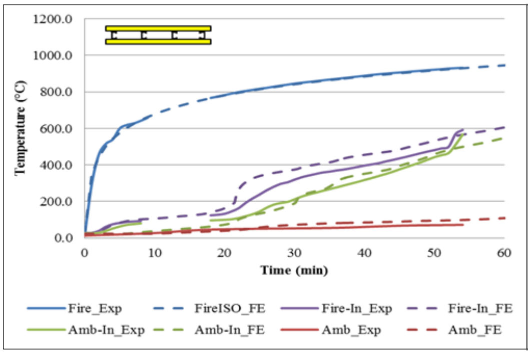


Figure 8: Model validation for plasterboard

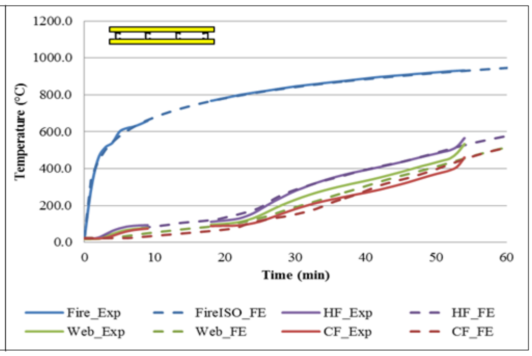


Figure 9: Model validation for studs

FRL of LSF Walls

The validated 3-D FE heat transfer model was used to predict the time-temperature profiles for the steel stud hot flange (HF) and the ambient side plasterboard (Amb) of LSF wall panels lined with single 16 mm lining made of the three gypsum plasterboards considered in this study. The idealized thermal properties proposed in Figures 2 to 4 for these three plasterboards were used as the thermal property inputs. The time-temperature profiles obtained from thermal FE analysis (Figure 10) show that the LSF wall panels lined with these three boards are likely to produce similar FRLs for load bearing and non-load bearing walls based on a hot flange limiting temperature of 500°C and an ambient side limiting temperature of 200°C.

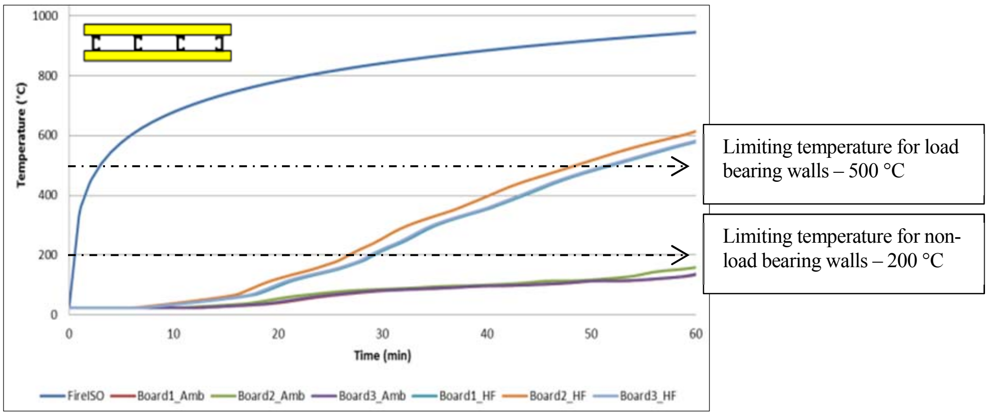


Figure 10: Time-temperature profiles of steel stud hot flange and ambient side plasterboard

DISCUSSION

The predicted time-temperature curves for LSF wall panels in Figure 10 show that the differences in time-temperature curves are small and appear to correlate well with the calculated k-factor profiles in Figure 6, i.e. k-factor profiles shifts up for LSF walls with higher FRL. Although all three board manufacturers claimed the same FRL, time-temperature profiles from FE analysis depicts that FRL of Board 2 is slightly lower compared to the other two. This corresponds to the lower most k-factor profile in Figure 6. Therefore, lower bound k-factor profile of Board 2 is proposed as the standard for the overall measure of the fire performance of plasterboards in LSF wall applications. The mass loss limitations stated earlier should also be considered when comparing any plasterboard against this proposed standard of k-factor profile.

The k-factor profile of any fire rated plasterboard, calculated using Equation 1, should lie above the curve proposed in Figure 11 for it to be used as lining material for LSF wall systems exposed to fire conditions. If part of the k-factor profile of a given plasterboard lies below the proposed standard in Figure 11, LSF walls lined with those boards should be tested according to the standard fire testing procedure given in AS 1530.4 [2] to determine the suitability for fire design applications. The plasterboards with the entire k-factor profile located above the proposed standard can be considered safe to use in LSF wall applications for fire design.

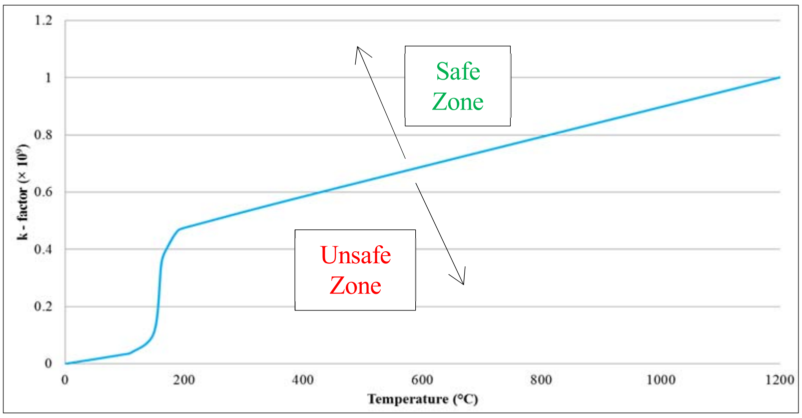


Figure 11: Proposed k-factor profile as a standard

CONCLUSIONS

This paper has presented the details of an investigation on setting minimum standards for fire protective boards used in load bearing and non-load bearing LSF wall panels. It included the chemical composition and thermal property characterisation of commonly used gypsum plasterboards from three Australian manufacturers. As an overall measure of the fire performance of plasterboards for LSF wall applications, a "k-factor" is proposed as a function of specific volumetric enthalpy, specific heat, density and thermal conductivity at elevated temperatures based on measured thermal properties. To investigate the relationship of the k-factor to the fire performance of LSF wall panels, a 3-D FE heat transfer model was developed and validated using fire test results. The k-factor profiles and the time-temperature curves from FE analysis showed a similar behaviour and hence it was concluded that FRL of LSF wall panels lined with the three gypsum plasterboards correlated well with the proposed k-factor. Finally, the lower bound of k-factor profiles for the three gypsum plasterboards was proposed as the standard of fire performance of plasterboards for use in LSF wall applications in fire design. Supplementary conditions on mass loss have also been proposed in this paper to allow for the extensive ablation and subsequent integrity failure of plasterboards due to excessive mass loss.

Further numerical studies and tests are currently under way using other boards with considerable differences in thermal properties to verify the suitability of the proposed k-factor profile.

ACKNOWLEDGEMENT

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